Forced Convection Radiators for Robotic and Human Exploration of Mars

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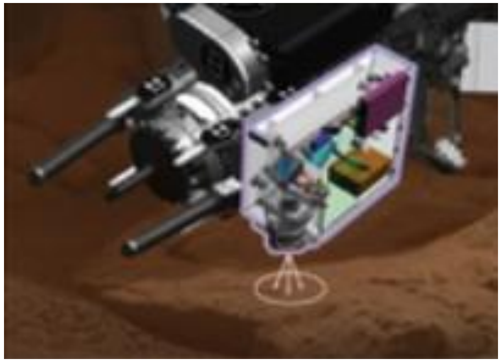
Outline

- Introduction
- Preliminary Estimates
- Test Set Up
- Test Method and Uncertainty
- Test Results
- Lessons Learned
- Future Work
- Conclusions

Introduction

- Current Mars landers and instruments rely on radiation and natural convection for thermal control.



Instruments [1]

Robotic Systems [2]

Manned Missions [3]

- Using forced convection has the potential to enable new thermal control architectures.

- This is especially appealing for Space Suits, which currently rely on consumables (water sublimation and evaporation) for heat rejection
  - ~ 400 W avg, 800 W peak [4,5]

Current State of the Art

Radiation (~5 W/m^2-K) + Natural Convection (~0.4 W/m^2-K) = 1.5 m^2 planar radiators

Proposed Innovation

Forced Convection (~3 W/m^2-K) + Finned Surfaces = 21.4 m^2 radiator area in a 0.5 x 0.5 x 0.1 m volume

But what about the density?

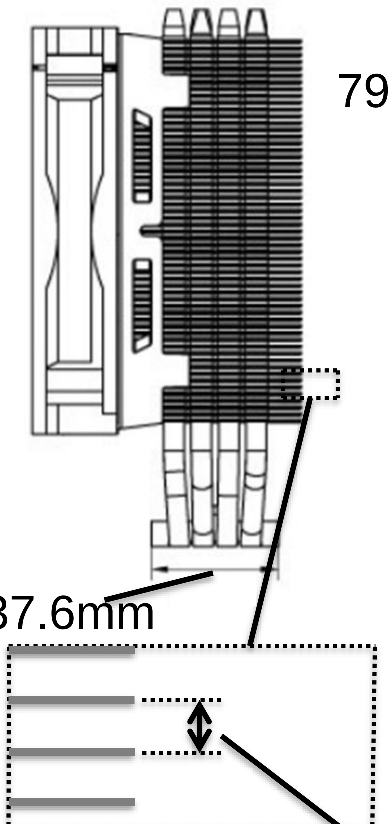
- Density of CO_2 on Mars is 50-100x smaller than the density of air on Earth
  - Depends on P, T, worst case ρ_{CO2} = 0.015 Kg/m^3 @ 10 °C and 6 torr
- What volume of gas can fans move?
  - 0.12 m x 0.12 m = 0.014 m^2 CPU Heat Sink Fan: 80 CFM [6]
  - 0.5 m x 0.5 m = 0.25 m^2 Box Fan: 2500 CFM [7]
  - Fans sweep a constant volume, so it makes sense that volumetric flow is approximately independent of pressure [8]
- Back of the envelope calculations suggest it's feasible to remove significant heat from a 30 °C hot side with a 10 °C ambient temperature, even at 10% efficiency.
  - Heat Rejection would be double for a 50 °C hot side

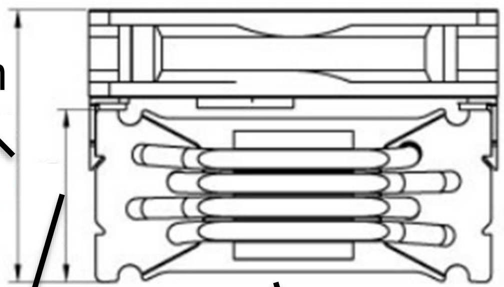
Fan Area	Volumetric Flow Rate		Velocity, V	Mass Flow Rate, $\dot{m}$	Mass Flow Conductance	Heat Rejection (T_h = 30 °C)	Fan Power $\sim\frac{1}{2}\dot{m}V^2/\eta$
(m^2)	(CFM)	(m^3/s)	(m/s)	(Kg/s)	(W/K)	(W)	(W)
0.014	80	0.038	2.7	0.00057	0.5	**10**	~ 0.02
0.25	2500	1.2	4.8	0.018	15	**300**	~ 2.1

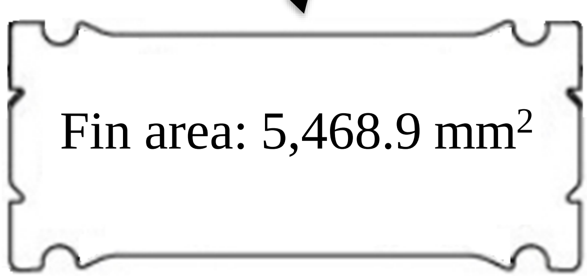
Experimental Goals

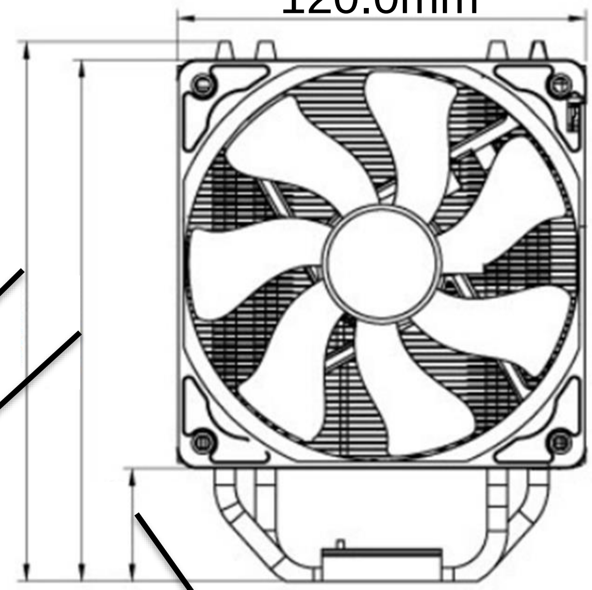
- Hypothesis # 1
  - Volumetric flow rate is roughly independent of pressure
- Hypothesis # 2
  - Forced convection heat transfer at Mars pressure is limited primarily by mass flow
- Hypothesis #3
  - Forced convection cooling is a competitive technology for Mars surface missions
    - Instruments
    - Rovers
    - Human Space Suits

Tested Heat Sink Dimensions









Fin spacing: 1.66 mm

Fin thickness: 0.34 mm

Fin count: 57

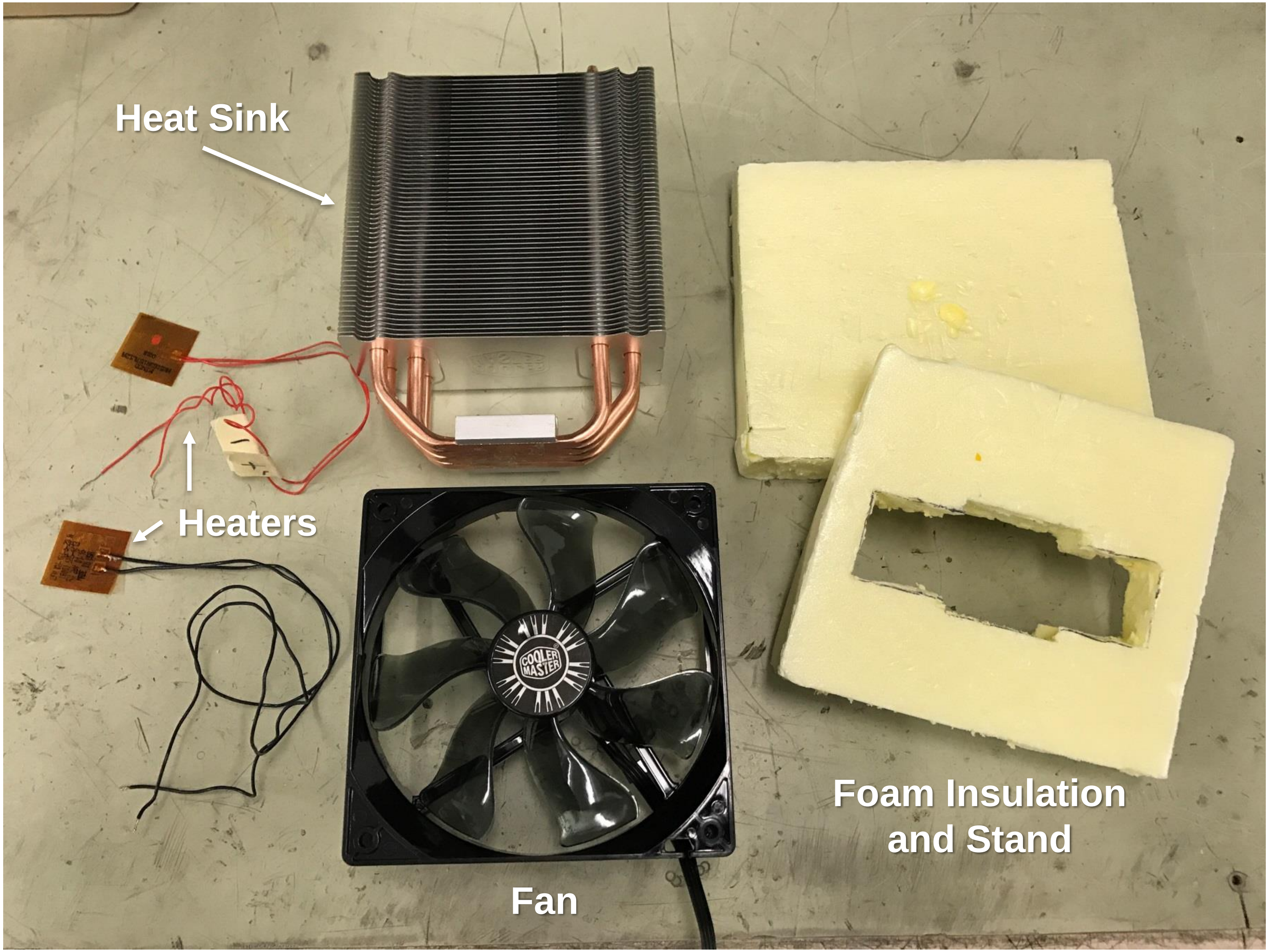
Two sides of convective surface area per fin

Total convective surface area of heat sink fins: **0.63 m²**

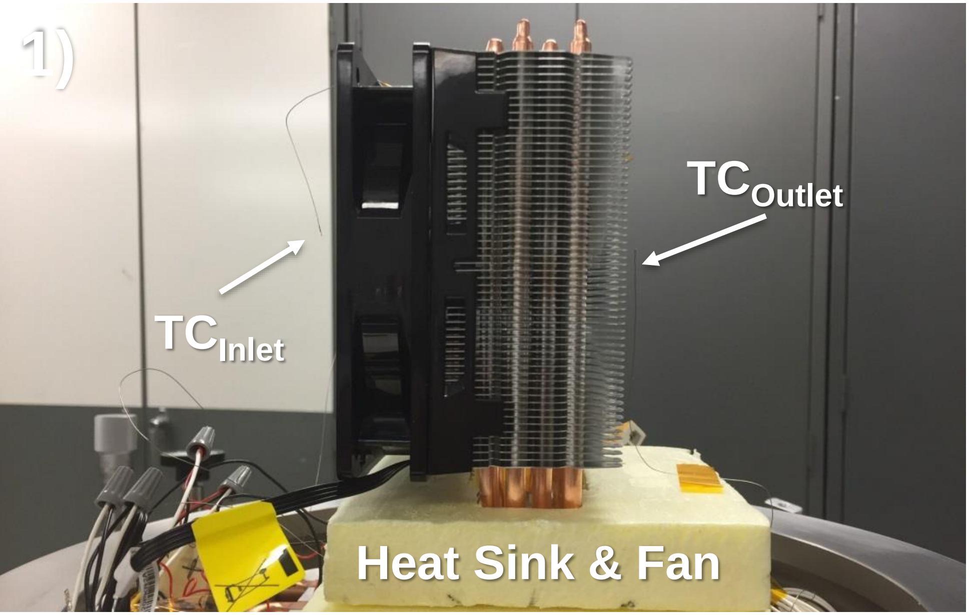
$G_{conv,expected}$ = hA = ~ (3 W/m²-K)(0.63 m²) = **1.9 W/K**

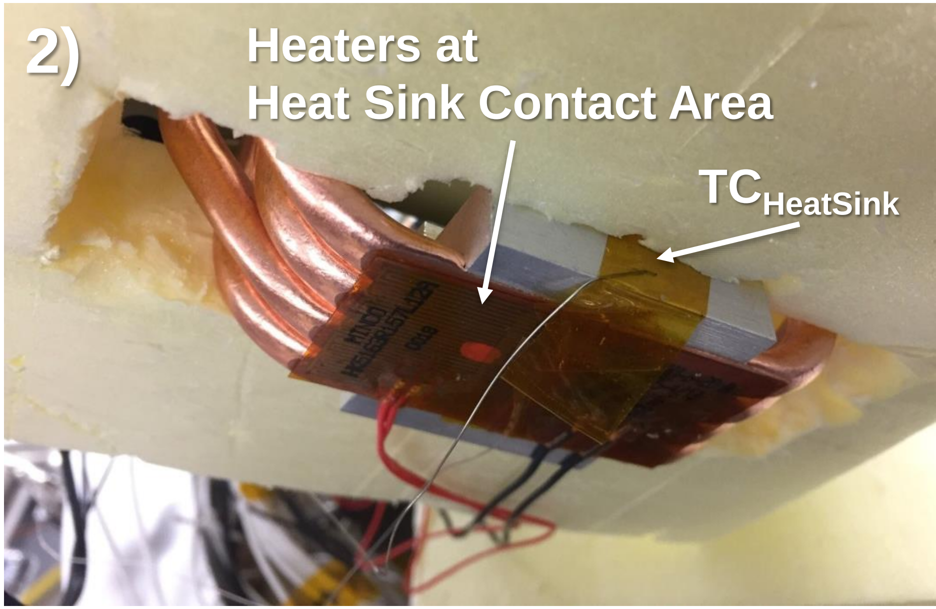
$G_{massflow,expected}$ = $\dot{m}c_p$ = ~ **0.5 W/K** (anticipated bottleneck)

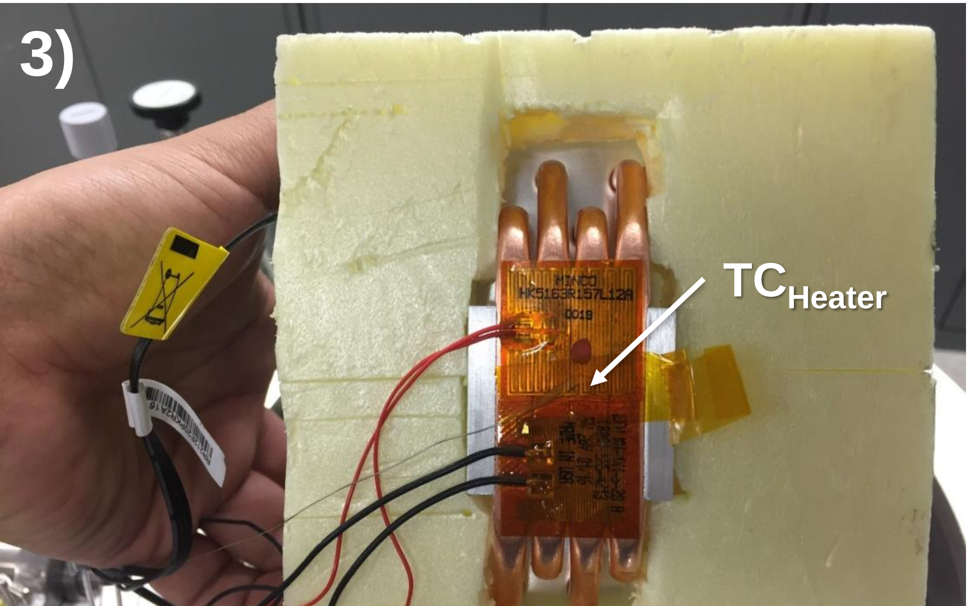
Test Equipment

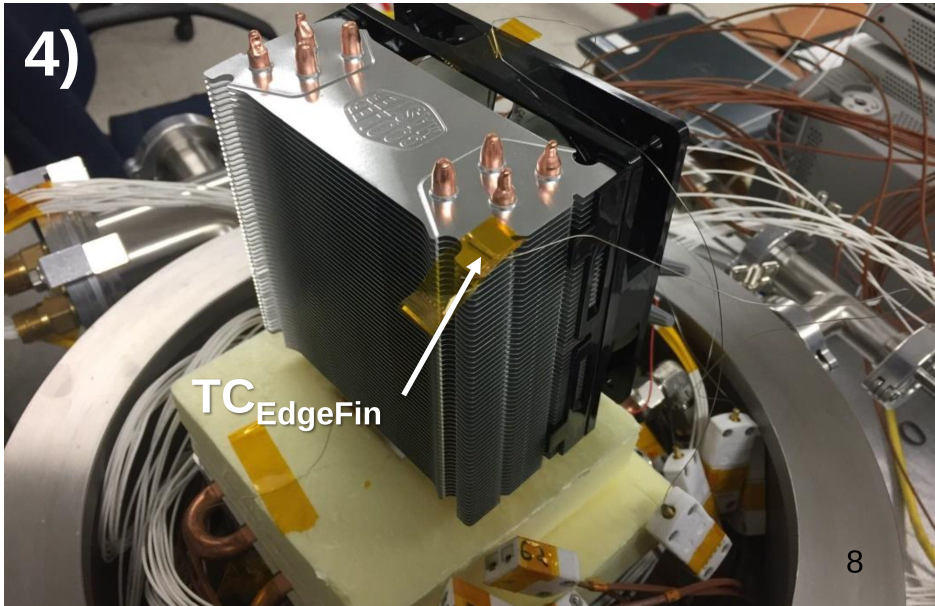


Thermocouple and Heater Set Up

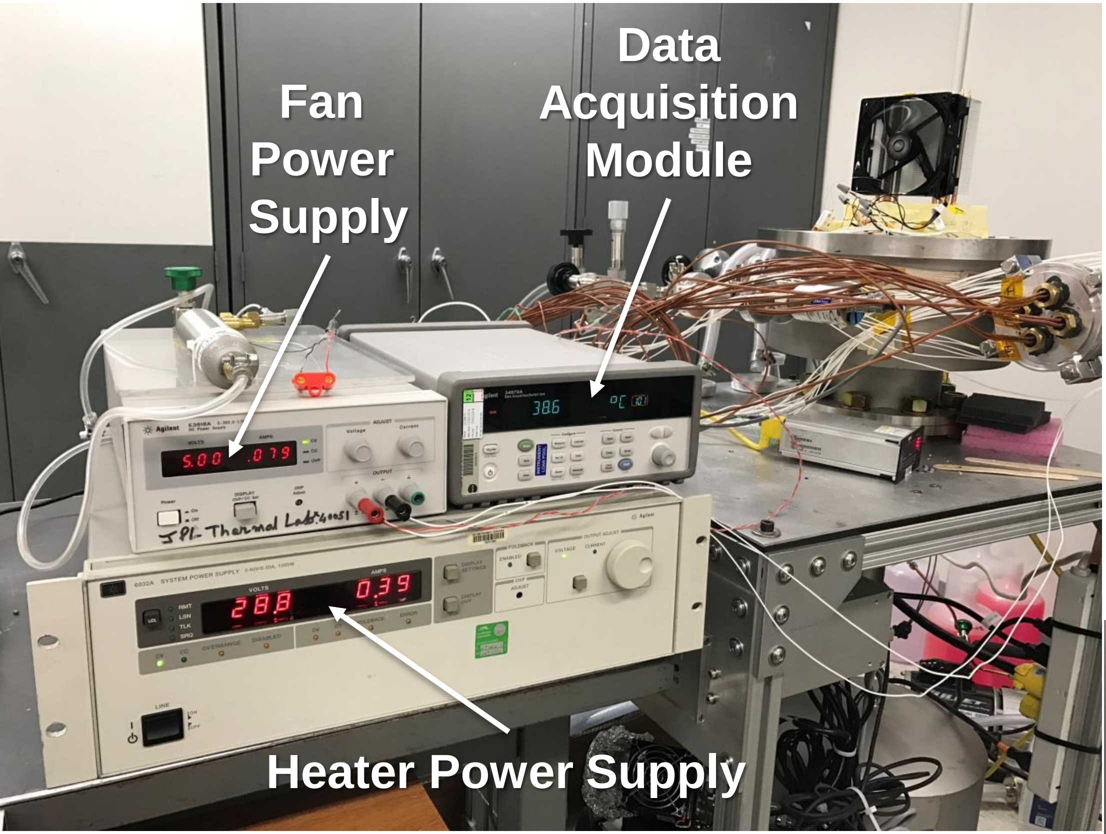




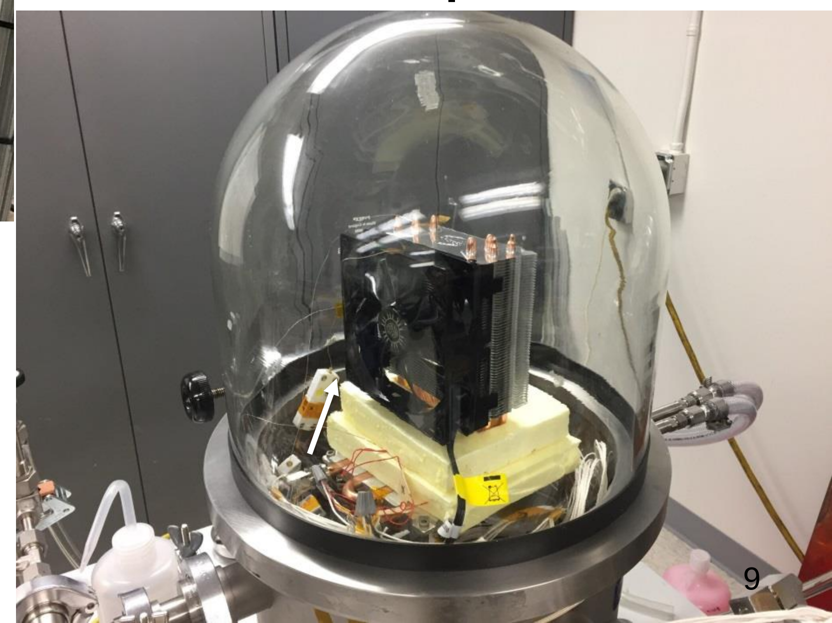




Test Set Up



Vacuum Chamber for Mars Atmospheric Test



Test Method and Uncertainty

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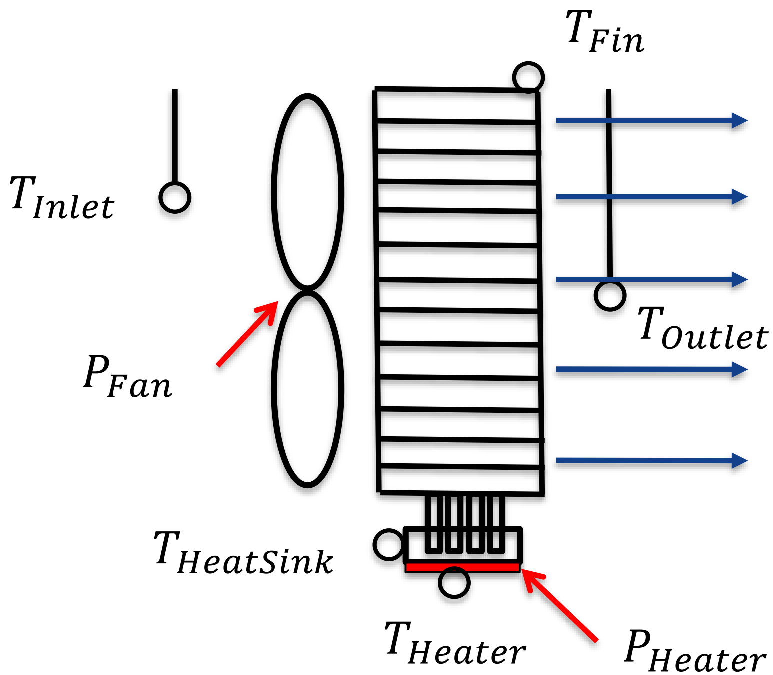
Relevant Equations:

- Conductance, $G = P_{Heater}/(T_{HeatSink} - T_{Inlet})$
- Mass Flow, $\dot{m} = (P_{Heater} + P_{Fan})/[c_p(T_{Outlet} - T_{Inlet})]$
- Velocity, $V = \dot{m}/\rho A$
- Flow Rate, $Q = VA$
- Fan Efficiency, $\eta = (\frac{1}{2}\dot{m}V^2)/P_{fan}$
  - *Note: Atypical definition for fan efficiency*



Heat Leaks

- Maximum heat loss through foam and wires is < 0.2 W (< 7 % error)

Uncertainty and Error Sources

- Typical TC uncertainty is +/- 1 °C, but all TCs were reading +/- 0.35 °C at ambient.
- Conductance uncertainty is low.
- Mass flow rate, velocity, volumetric flow rate, and fan efficiency uncertainty is high:
  - Uniform Velocity & Temperature Assumption
    - Uncertainty is not Quantifiable!!!
  - ΔT between T_{Inlet} and T_{Outlet}:
    - 2.4 to 6.3 °C for 760 Torr Air
      - < 30 % error assuming +/- 0.35 °C
    - 9.6 to 17.4 °C for 6 Torr CO_2
  - Fan is intended to be duty cycled but was powered with DC voltage.
    - Might affect fan power estimates.
  - Fan efficiency is typically defined using pressure drop, but the pressure drop was not measured.

Test Matrix

Run	Pressure (torr)	Gas	Fan Voltage (V)	Fan Power (W)	Heater Power (W)
1	760	Air	0	0	13.8
2	760	Air	5	0.4	37.0
3	760	Air	9	2.0	40.1
4	760	Air	12	4.0	40.5
5	5 to 7	CO_2	0	0	3.2
6	5 to 7	CO_2	5	0.3	3.2
7	5 to 7	CO_2	9	1.3	3.2
8	5 to 7	CO_2	12	2.5	3.2
9	5 to 7	CO_2	12	2.5	6.0

Test Procedure

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1. **Mars Test:** Use air pump to pump out all air in chamber. Pump CO_2 into chamber until 5 to 7 torr pressure is reached. Continually monitor pressure. Pump excess CO_2 out to maintain 5 to 7 torr pressure as necessary.

2. **All Tests:** Power on heaters and adjust power supply to bring heaters to steady state temperature. Steady state is defined as 20 minutes with < 0.2 C temperature change.

3. Record data every 30 seconds.

4. Power on fan, setting power supply to 5V. Adjust heater voltage and current as needed and run to steady state.

5. Set fan voltage to 9V. Adjust heater voltage and current as needed and run to steady state.

6. Set fan voltage to 12V. Adjust heater voltage and current as needed and run to steady state.

7. Power down heater voltage and current before shutting off power supply. Power down fan voltage and current before shutting off power supply. Power off DAQ.

8. **Mars Test:** Vent chamber until atmospheric pressure is reached.

Earth Atmospheric Case Test Data

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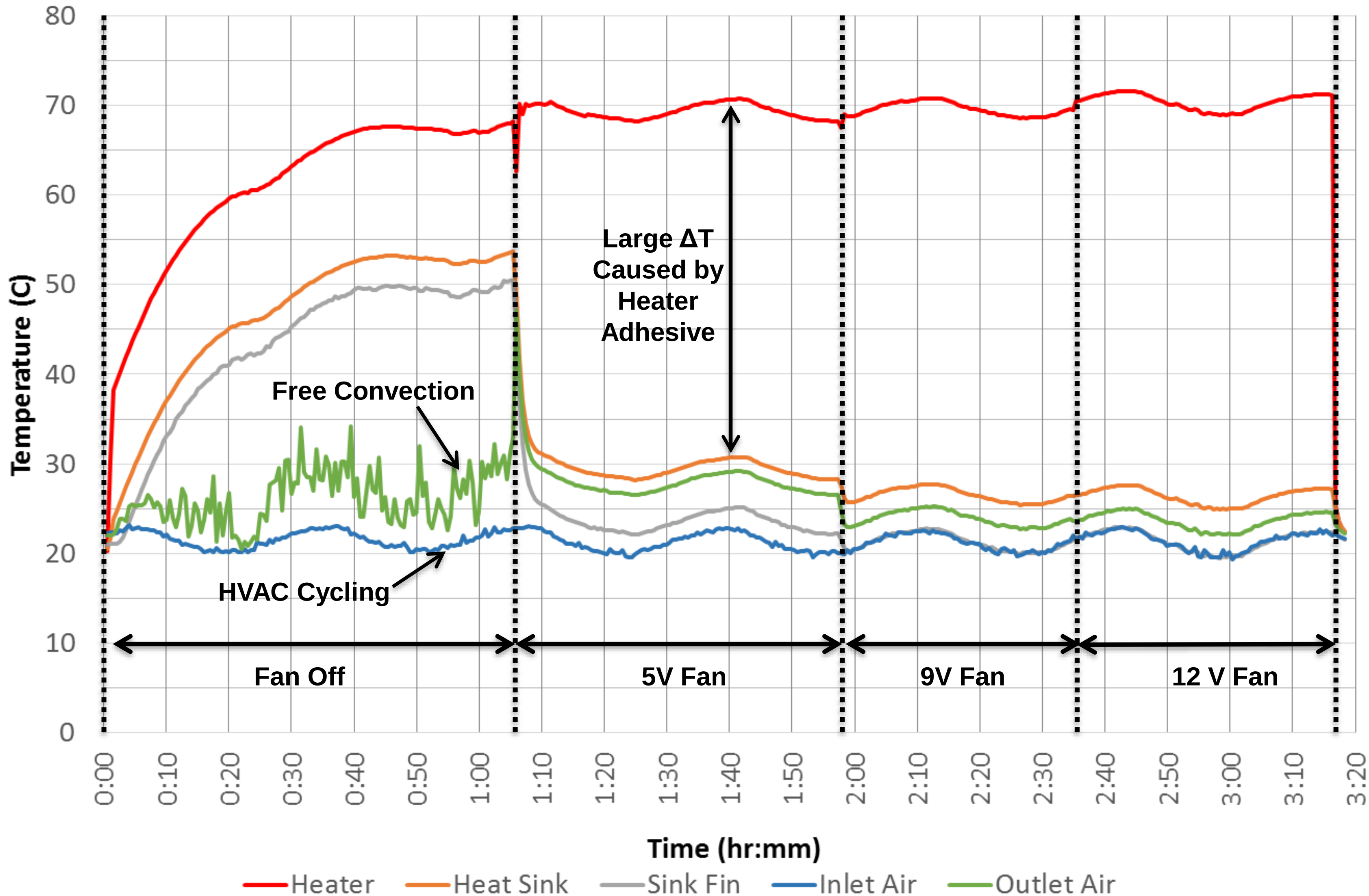

Mars Atmospheric Case Test Data

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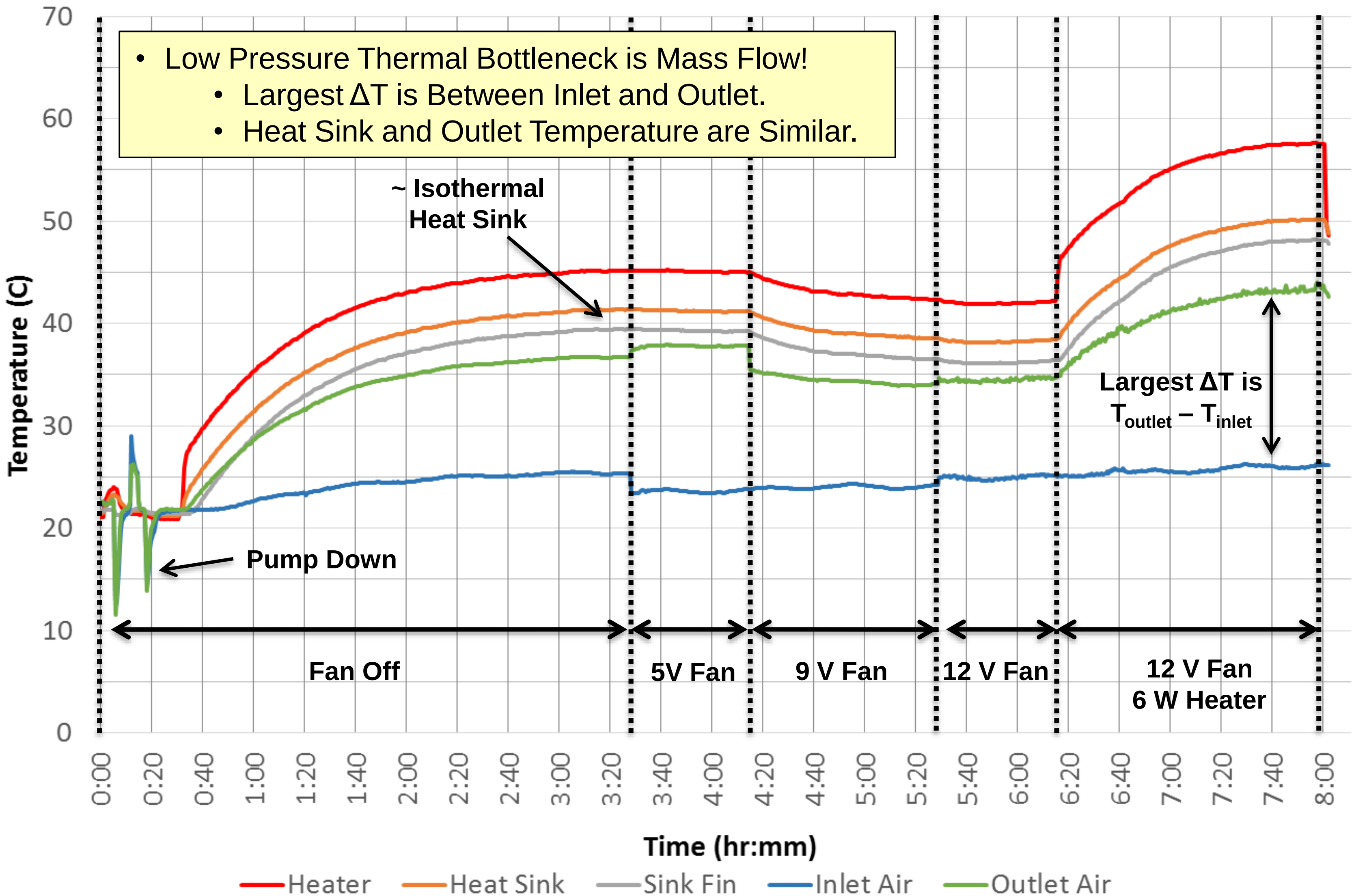

Conductance Results

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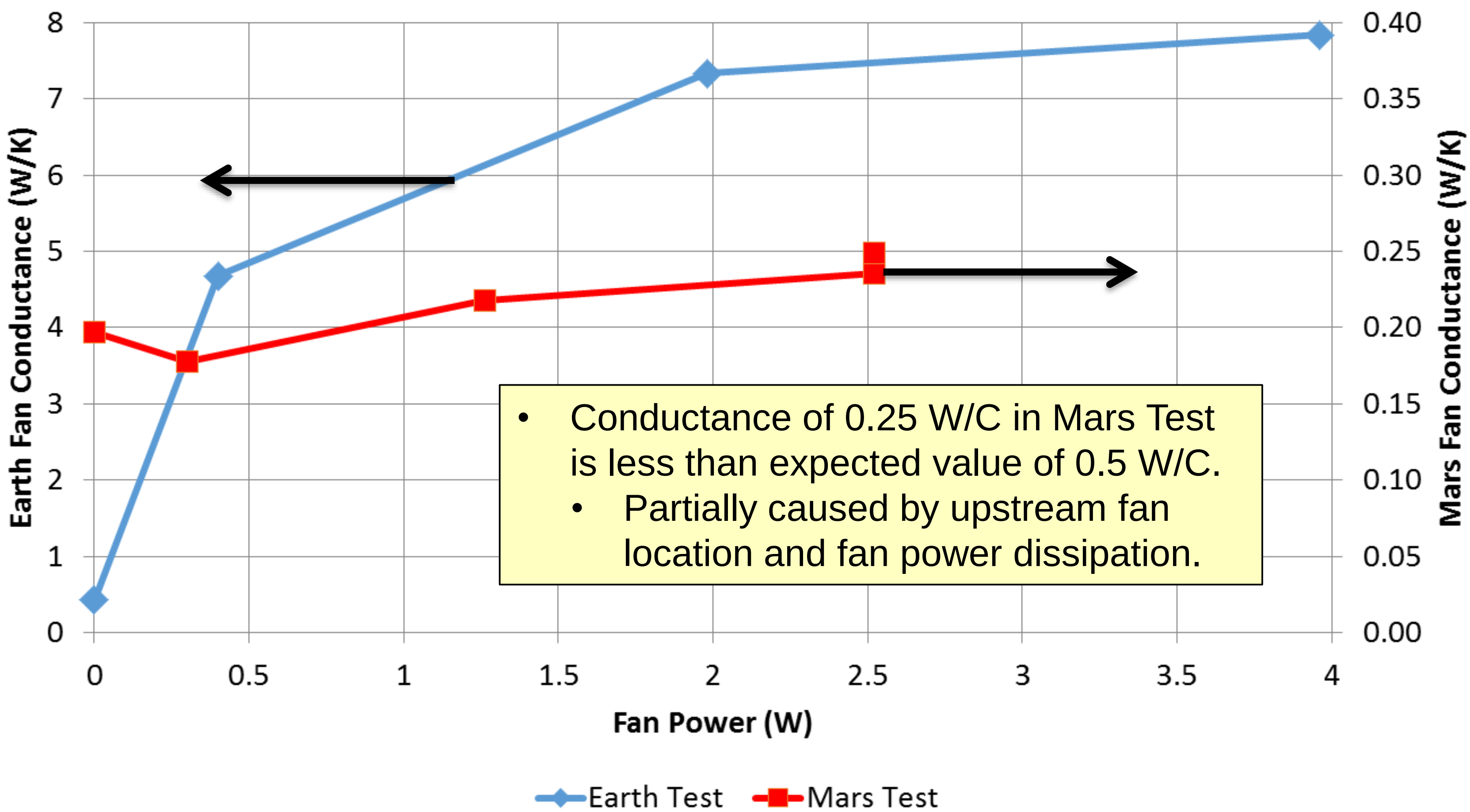
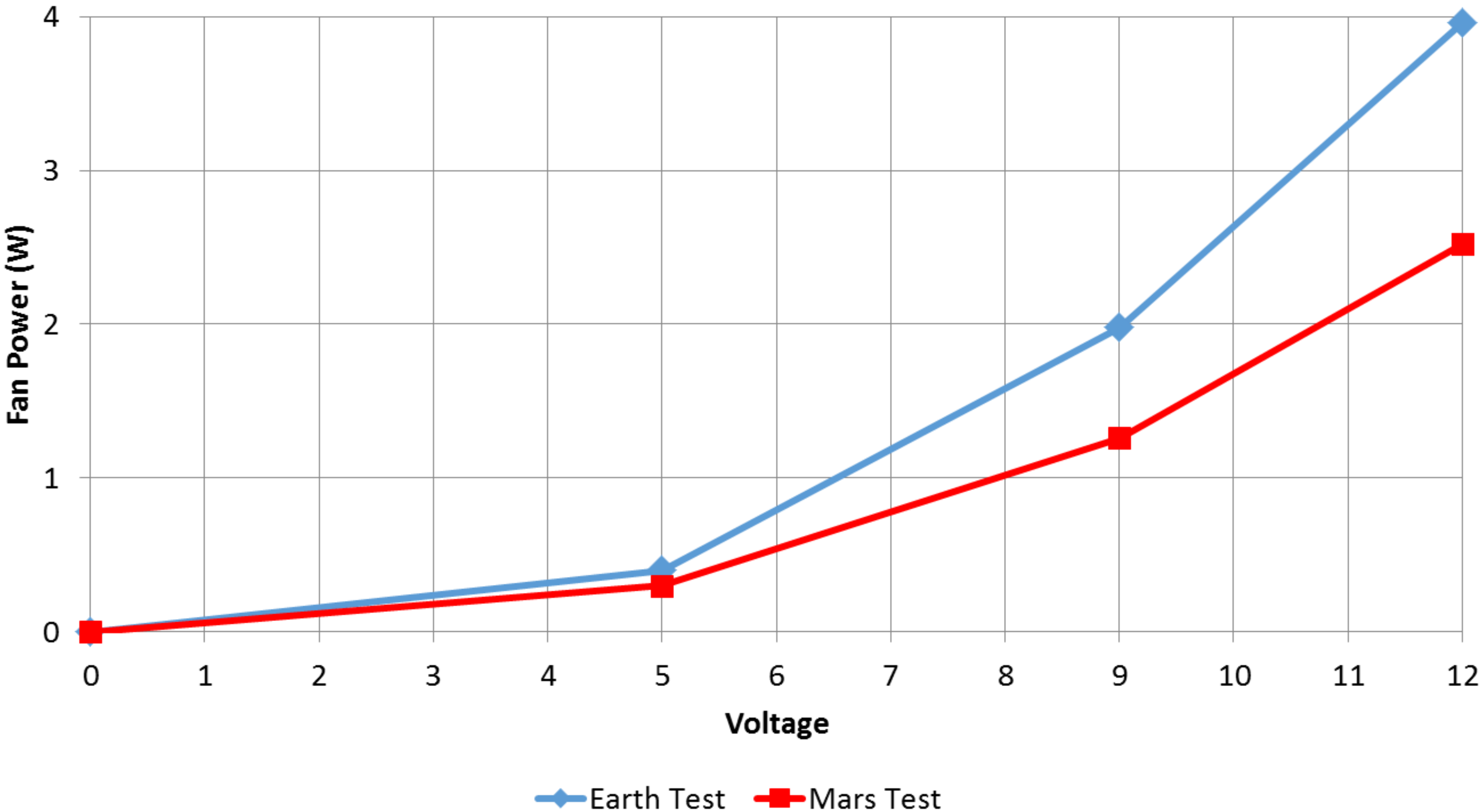
- Fan significantly increases heat removal in 760 Torr Air.
- Fan does not significantly change heat removal in 6 Torr CO_2.



- Conductance of 0.25 W/C in Mars Test is less than expected value of 0.5 W/C.
  - Partially caused by upstream fan location and fan power dissipation.

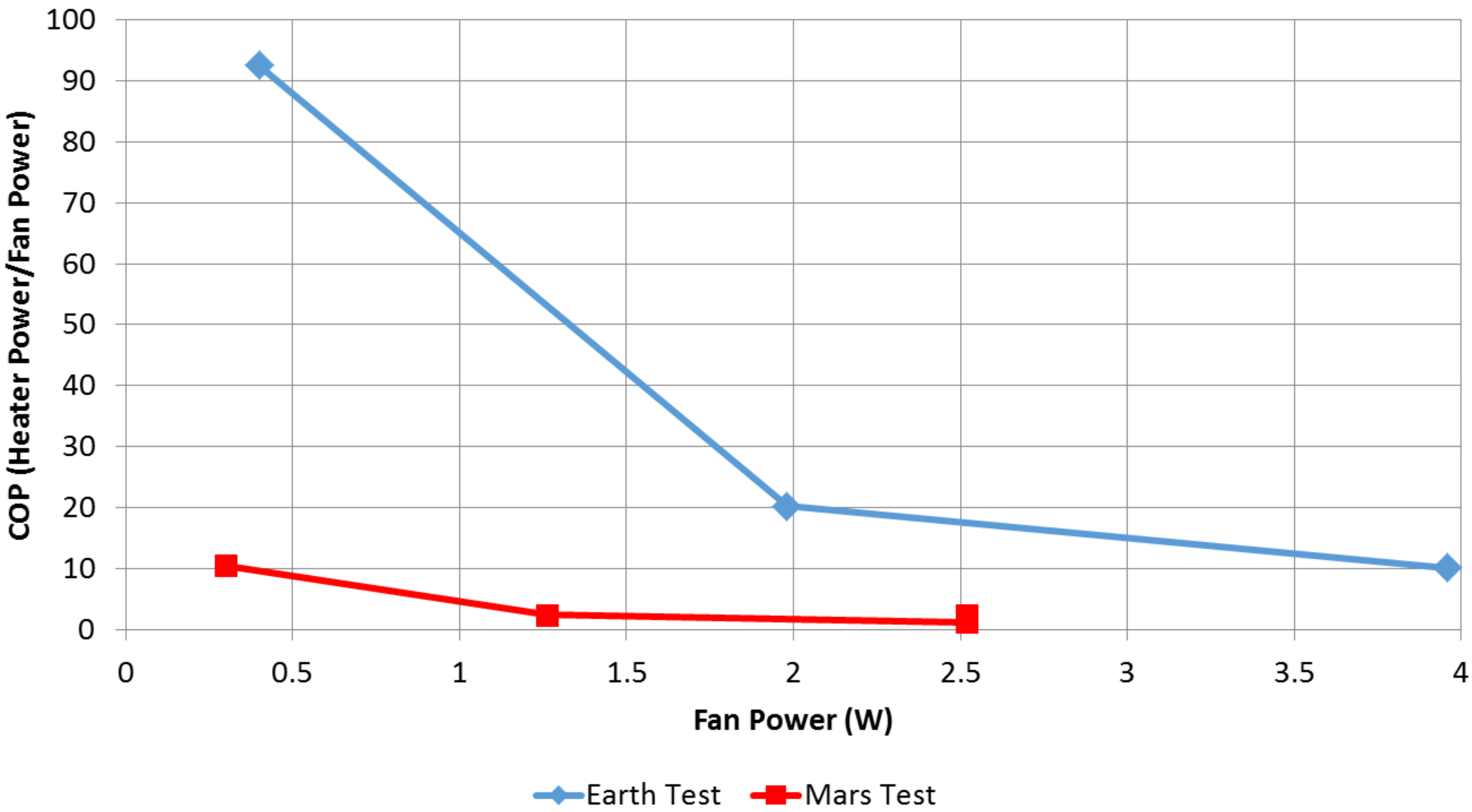
Fan Voltage and Power

- Fan Power does not decrease appreciably at lower densities.
  - Keep in mind that we are using DC voltage instead of PWM control.



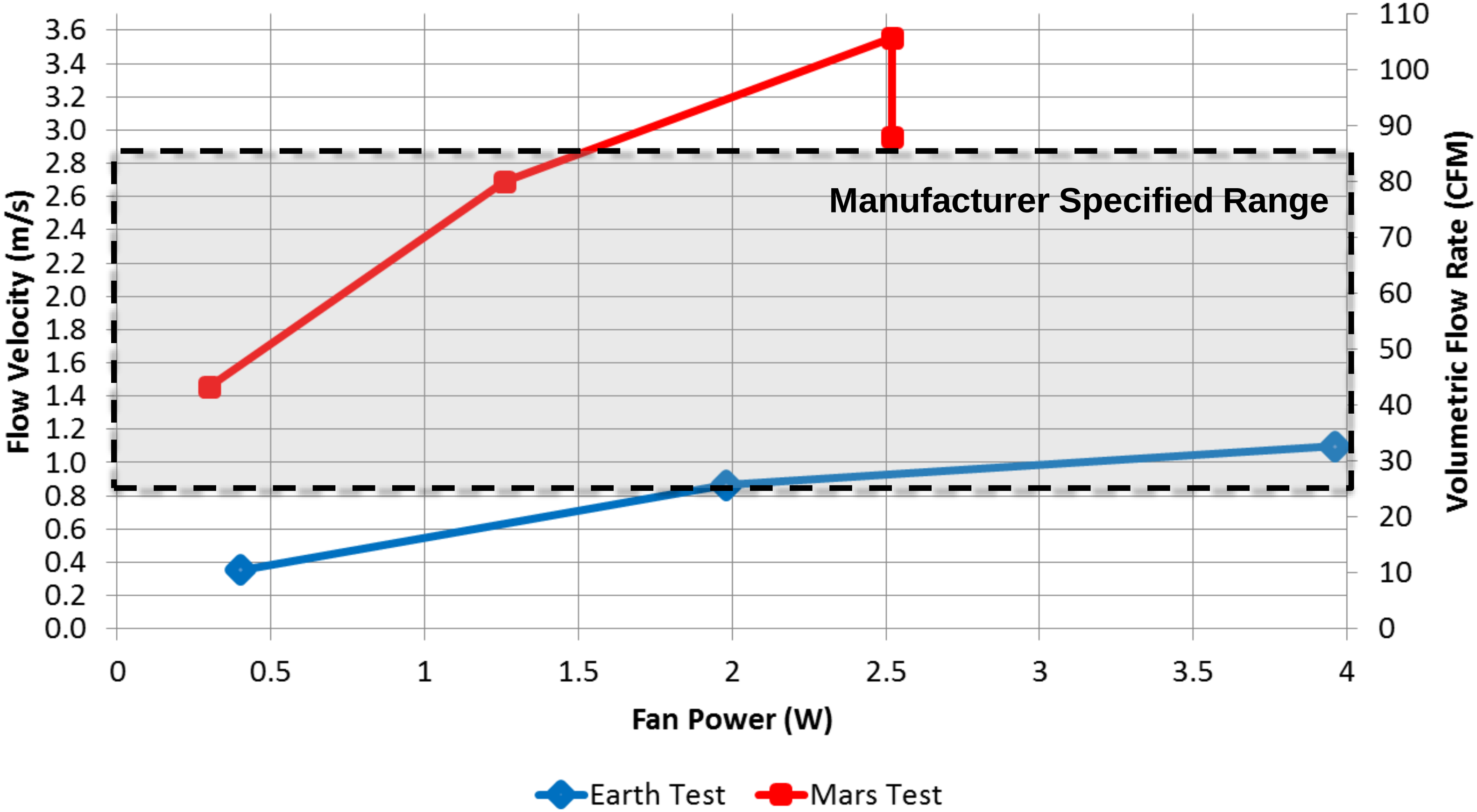
Heater/Fan Coefficient of Performance

- Fans provide efficient means of heat removal in 760 Torr Air.
- Power needed to run fan approaches the heat removed by the fan in 6 Torr CO_2.



Volumetric Flow Rate and Velocity

- Estimated flow rates in 760 Torr Air and 6 Torr CO_2 compare well with manufacturer specifications.
  - 760 Torr Air flow rates are on the low side
    - One possible explanation is that fan performance specs are for a fan without heat sink.
    - Another possible explanation is the uniform velocity assumption (previously discussed).
- Estimated flow rate and velocity seems to increase as the pressure decreases.



Fan Efficiency

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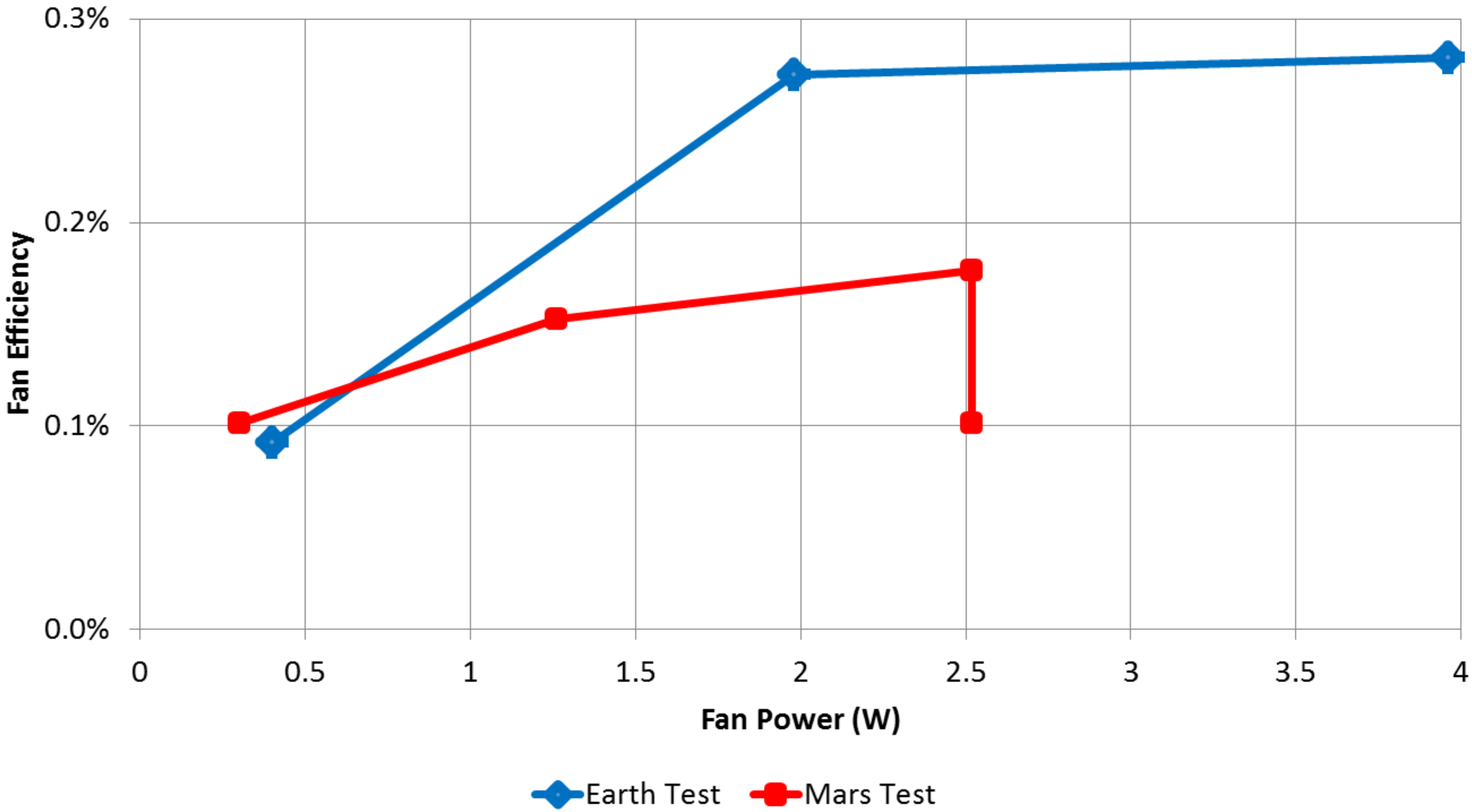
- Fan Efficiency is much lower than expected
  - Note that we are using a non-typical definition for fan efficiency
    - Our Definition: $\eta = (\frac{1}{2}\dot{m}V^2)/P_{fan}$
    - Typical Definition: $\eta = Q_{flow}\Delta P/P_{fan}$



Conclusions

- Hypothesis # 1
  - Volumetric flow rate is roughly independent of pressure
  - **Confirmed**
- Hypothesis # 2
  - Forced convection heat transfer at Mars pressure is limited primarily by mass flow
  - **Confirmed**
- Hypothesis # 3
  - Forced convection cooling is a competitive technology for Mars surface missions
  - **Not Confirmed – More Research is Needed**
    - Fans need to use less power: fan efficiency and COP is poor at 6 Torr.
    - Locating the fan downstream from the heat exchanger would ensure that the coldest air enters the heat exchanger.
    - Increased flow rates also would increase the thermal conductance.
    - Direct measurement of fan speed and flow velocity using a tachometer and anemometer would benefit any future experiments.

Lessons Learned

- Engineering projects, no matter how small, need research, training, and a plan.
  - Knowing how to communicate with mentors is vital to success.

- Better understanding of heat transfer.

- Taking on this internship in the fall or spring is a significant time commitment (equivalent to 2 or 3 college courses of lecture time).

- It appears that forced convection would be quite a challenge on Mars and other low pressure environments (like the upper Earth atmosphere).

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Experimental and Calculated Data

- All data shown here is steady state data averaged over a period of 10 minutes.

Run	Pressure (torr)	Atmos-phere	Fan Voltage (Volts)	Fan Current (Ampere)	Fan Power (Watts)	Heater Voltage (Volts)	Heater Current (Ampere)	Heater Power (Watts)	Heater Temp (deg C)	Heat Sink Temp (deg C)	Fin Temp (deg C)	Inlet Temp (deg C)	Outlet Temp (deg C)	Specific Heat (J/kg-K)	Density (kg/m^3)	Conduct-ance (W/K)	Mass Flow (kg/s)	Flow Velocity (m/s)	Volume Flow (m^3/s)	Volume Flow (CFM)	Fan Efficiency
1	760	Earth air	0	0	0	32.0	0.43	13.8	67.34	52.87	49.40	20.66	25.31	1005	1.20	0.43					
2	760	Earth air	5	0.08	0.4	52.9	0.70	37.0	69.59	29.62	23.79	21.71	28.00	1005	1.20	4.68	0.0059	0.34	0.0049	10.44	0.09%
3	760	Earth air	9	0.22	1.98	54.9	0.73	40.1	69.69	26.61	21.33	21.14	24.03	1005	1.20	7.33	0.0145	0.84	0.012	24.87	0.26%
4	760	Earth air	12	0.33	3.96	55.5	0.73	40.5	70.15	26.16	21.03	20.99	23.39	1005	1.20	7.83	0.0184	1.07	0.015	31.64	0.27%
5	6	CO_2	0	0	0	15.03	0.21	3.16	45.13	41.33	39.41	25.32	36.68	844	0.014	0.20					
6	6	CO_2	5	0.06	0.3	15.03	0.21	3.16	45.06	41.20	39.27	23.46	37.77	844	0.014	0.18	0.00029	1.42	0.020	42.06	0.10%
7	6	CO_2	9	0.14	1.26	15.03	0.21	3.16	42.37	38.57	36.53	24.09	33.99	844	0.014	0.22	0.00053	2.62	0.037	77.75	0.14%
8	6	CO_2	12	0.21	2.52	15.03	0.21	3.16	41.90	38.14	36.09	24.76	34.38	844	0.014	0.24	0.00070	3.47	0.049	102.73	0.17%
9	6	CO_2	12	0.21	2.52	20.7	0.29	6.00	57.55	50.12	48.12	26.05	43.42	844	0.014	0.25	0.00058	2.88	0.040	85.48	0.10%

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Questions?